

Keplerian rotation of our Galaxy?

P. Gnaciński¹ and T. Młynik²

¹Institute of Theoretical Physics and Astrophysics,
Faculty of Mathematics, Physics and Informatics,
University of Gdańsk,
80-308 Gdańsk, Poland
email: *fizpg@univ.gda.pl*

²Student at the University of Gdańsk.

March 7, 2017

Abstract

It is common to attribute a flat rotation curve to our Galaxy. However Galazutdinov *et al.* (2015) in a recent paper have obtained a Keplerian rotation curve for interstellar clouds in outer parts of the Galaxy. They have calculated the distances from equivalent widths of interstellar CaII lines. The radial velocity was also measured on the interstellar CaII absorption line.

We verify the result by Galazutdinov *et al.* (2015) basing on observations of old open clusters. We propose, that the observations of flat and Keplerian rotation curves may be caused by the assumption of circular orbits. The application of formulas derived with the assumption of circular orbits to elliptical ones may mimics the flat rotation curve. The interstellar clouds with cross-sections larger than stars may have almost circular orbits, and the derived rotation curve will be Keplerian.

Key words: *Galaxy kinematics and dynamics; dark matter*

1 Introduction

Our Galaxy is usually thought to have a flat rotation curve. The flat rotation curves of galaxies are usually explained assuming existence of dark matter. The MOND (MOdified Newtonian Dynamics) models are less popular. However, some galaxies have Keplerian rotation curves which falls as $\sim 1/\sqrt{r}$ in the outer parts of the galaxies. In a sample of 45 galaxies analyzed by Honma & Sofue (1997) 11 have Keplerian rotation curve.

A compilation of rotation velocities observed in our Galaxy was made by Sofue *et al.* (2009). They have transformed the rotational velocities from various sources to common parameters $R_\odot = 8$ kpc and $v_\odot = 200$ km/s. In this paper we adopted the recently obtained solar velocity

$v_\odot = 240$ km/s (Honma *et al.*, 2015, 2012; Sofue, 2016). The rotation curves and rotational velocities of individual objects were recalculated using $v_\odot = 240$ km/s.

Rotation velocities from Sofue *et al.* (2009), derived with tangent point method or from radial velocity, are shown on Fig. 2(a).

The absence of dark matter in solar neighborhood was postulated by Moni Bidin *et al.* (2012). Their result is based on stellar kinematics in direction perpendicular to the galactic plane. However, their calculation leads to a flat rotation curve.

The recent paper by Galazutdinov *et al.* (2015) shows a Keplerian rotation curve of our Galaxy. They have based on distances and radial velocities derived from interstellar CaII absorption lines. The aim of this paper is to reconcile the flat rotation curve from Sofue *et al.* (2009) and the Keplerian rotation derived by Galazutdinov *et al.* (2015).

2 Old open clusters

In order to verify the result by Galazutdinov *et al.* (2015) we have analyzed the rotation velocity of old open clusters (age greater than 10^9 years) located in the outer part of the Galaxy $l \in (90^\circ, 270^\circ)$. All analyzed open clusters are located close to the galactic plane $|b| < 20^\circ$.

The rotational velocity was calculated from observed radial velocity. The heliocentric radial velocity v_h was first transformed to the local standard of rest (LSR)

$$v_{LSR} = v_h + U_\odot \cos b \cos l + V_\odot \cos b \sin l + W_\odot \sin b \quad (1)$$

using the Sun velocity $(U_\odot, V_\odot, W_\odot) = (11.1, 12.24, 7.25)$ km/s from Schönrich *et al.* (2010). The rotational velocity was calculated using formula derived for circular orbits (eg. Bhattacharjee *et al.*, 2014)

$$v(r) = \frac{r}{R_\odot} \left(\frac{v_{LSR}}{\sin l \cos b} + v_\odot \right). \quad (2)$$

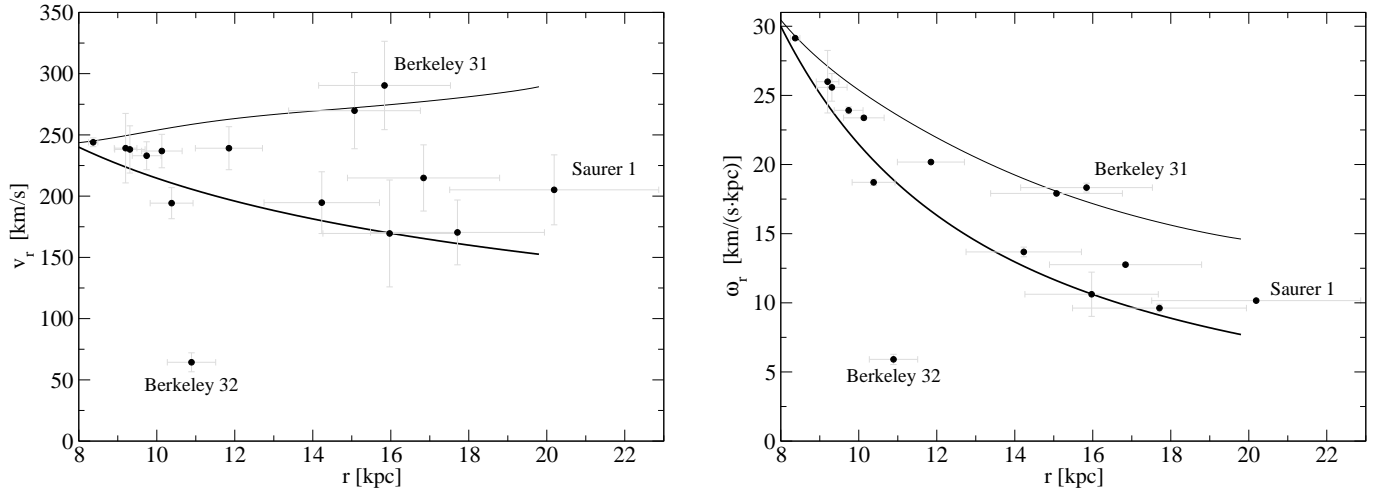


Figure 1: Rotation velocity of old open clusters (left panel) versus Galactocentric distance. The right panel show the same data as angular rotation velocity. The lines show the model of flat rotation curve by Sofue *et al.* (2009) and the Keplerian rotation curve (both for $v_{\odot}=240$ km/s).

In this formula r is the projection of galactocentric distance on the galactic plane

$$r = \sqrt{R_{\odot}^2 + d^2 \cos^2 b - 2R_{\odot}d \cos b \cos l}. \quad (3)$$

The clusters with galactic longitude $l = 180^{\circ} \pm 20^{\circ}$ were excluded from our sample, because the $\sin l$ in the denominator of formula 2 leads to unphysical (i.e. negative) rotation velocities.

At least some old open clusters have nearly circular orbits. The five old open clusters analyzed by Carraro (1994) have eccentricities less than 0.14, with two clusters having eccentricities as low as $e = 0.03$. We have collected open clusters data from the literature (see table 1), and determined the rotation velocity using formulas 1 and 2. The open clusters linear velocity, as well as the angular velocity is presented on figure 1. The advantage of the angular velocity is, that its error does not depend from the distance to cluster, which is known with little accuracy.

The distances to open clusters analyzed by Carraro *et al.* (2007) were determined by fitting a isochrone to the CMD (colour-magnitude diagram). The largest error of distance in their sample of five open clusters is 21%. The distance to Saurer 1 was also determined by fitting a isochrone to the CMD. For the open cluster Berkeley 31 we were unable to track down the method used to determine distances. The distance of 8.3 kpc to Berkeley 31 was cited by Carraro *et al.* (2007), but other distances can be found in the literature: the distance 3.68 kpc was cited by Janes & Phelps (1994), and 5.2 ± 0.5 kpc was determined by fitting isochrones to the CMD (Guetter, 1993). Distances to other clusters were determined using the synthetic CMD method (Tosi *et al.*,

1991), but the errors of distances were not given. The authors state, that the synthetic CMD method is more accurate than the isochrone fitting to CMD. Therefore we have adopted the relative error of distances equal to 21% for all analysed open clusters.

The distances to open clusters are known with better accuracy, than the distances to HII regions, which were used by Sofue *et al.* (2009) to construct his rotation curve. The distances to HII regions were determined using optical spectrophotometric methods (Fich *et al.*, 1989). The maximal relative error of their distances is 40%, and the average error is 25%.

Figure 1 presents rotational velocity of old open clusters. The same data is presented as angular velocity, because angular velocity error does not depend on distance error. Therefore we have checked the agreement between open clusters velocity and flat/Keplerian rotation curves with the angular velocity data. Because errors of the angular velocity are negligible as compared to distance errors we have analyzed the data as a $r(\omega)$ function. We have computed

$$\chi^2 = \sum_i \left(\frac{r_i - r(\omega_i)}{\sigma_i} \right)^2. \quad (4)$$

For Keplerian rotation curve we got $\chi^2 = 30.4$, while for the flat rotation we have $\chi^2 = 377.9$. The angular velocity of analyzed open clusters agrees with the Keplerian rotation curve at the significance level $\alpha = 0.005$. The open cluster Berkeley 32 was excluded from this analysis.

Cluster	radial velocity [km/s]	stars	ref.	l [°]	b [°]	dist [pc]	Age [log yr]	ref.	r [kpc]	$\omega(r)$ [km/(s-kpc)]	v(r) [km/s]
Berkeley 20	75.51 ± 4.85	9	a	203.483	-17.373	8710	9.763	a	16.0 ± 1.7	10.6 ± 1.6	169.5 ± 43.6
Berkeley 25	134.30 ± 1.62	4	e	226.612	-9.700	11400	9.699	e	17.7 ± 2.2	9.6 ± 0.3	170.4 ± 26.4
Berkeley 31	55.80 ± 1.13	2	o	206.254	5.120	8300	9.301	e	15.8 ± 1.7	18.3 ± 0.3	290.4 ± 36.1
Berkeley 32	105.00 ± 1.40	9	m	207.950	4.400	3162	9.720	n	10.9 ± 0.6	5.9 ± 0.4	64.3 ± 7.8
Berkeley 66	-50.65 ± 0.07	2	a	139.434	0.218	4570	9.580	a	11.9 ± 0.9	20.2 ± 0.0	239.1 ± 17.6
Berkeley 73	95.70 ± 0.57	2	e	215.278	-9.424	9800	9.176	e	16.8 ± 2.0	12.8 ± 0.1	214.9 ± 27.0
Berkeley 75	94.60 ± 0.35	1	e	234.307	-11.188	9100	9.602	e	15.1 ± 1.7	17.9 ± 0.1	269.8 ± 31.1
Cr 110	40.00 ± 1.00		d	209.650	-1.980	1950	9.230	d	9.7 ± 0.4	23.9 ± 0.3	233.0 ± 11.4
King 11	-35.00 ± 16.0		l	117.160	6.480	2198	9.615	n	9.2 ± 0.3	26.0 ± 2.3	239.2 ± 28.4
NGC 2243	61.00 ± 1.00		i	239.480	-18.010	3532	9.681	c, i	10.1 ± 0.5	23.4 ± 0.2	236.8 ± 13.6
NGC 2506	83.70 ± 1.40	4	f	230.560	9.940	3311	9.230	j, f	10.4 ± 0.6	18.7 ± 0.2	194.3 ± 12.7
NGC 6939	-18.98 ± 0.19	26	k	95.900	12.300	1820	9.114	b	8.4 ± 0.1	29.1 ± 0.0	244.0 ± 3.6
Pismis 2	49.20 ± 7.80	9	h	258.850	-3.340	3467	9.041	g	9.3 ± 0.4	25.6 ± 1.0	238.2 ± 19.3
Saurer 1	104.60 ± 0.30	2	p	214.689	7.386	13200	9.699	e	20.2 ± 2.7	10.2 ± 0.1	205.2 ± 28.6
Tombaugh 2	120.51 ± 2.19	37	a	232.832	-6.880	7950	9.204	a	14.2 ± 1.5	13.7 ± 0.3	194.7 ± 25.2

Table 1: Data of old open clusters and calculated velocities. If the error of radial velocity was not given we assumed 1 km/s. References: a - Andreuzzi *et al.* (2011); b - Andreuzzi *et al.* (2004); c - Bonifazi *et al.* (1990); d - (Bragaglia *et al.*, 2006, and references therein); e - (Carraro *et al.*, 2007, and references therein); f - Carretta *et al.* (2004); g - Di Fabrizio *et al.* (2001); h - Friel *et al.* (2002); i - Gratton *et al.* (1994); j - Marconi *et al.* (1997); k - Milone (1994); l - Scott *et al.* (1995); m - Sestito *et al.* (2006); n - Tosi *et al.* (2007); o - Yong *et al.* (2005); p - Carraro *et al.* (2004).

3 Non-circular orbits

The source of discrepancy in rotation curve determinations may be the assumption of circular orbits. We have assumed elliptical orbits as the simplest model of non-circular orbits. We checked if the assumption of stars on elliptical orbits is consistent with observed radial velocities. We have analyzed radial velocities of K and M giants in the Galactic anticenter from the CORAVEL spectrograph given by Famaey *et al.* (2005). Stars in binary systems have been removed from the analyzed sample. Regardless of the size of square centered on the Galactic anticenter the standard deviations of radial velocities can not be explained assuming circular orbits (Table 2). We obtain standard deviation of radial velocities similar to observed ones, assuming elliptical orbits with eccentricities uniformly distributed in the range 0–0.6 in the outer parts of our Galaxy. So, the assumption of non-circular orbits is consistent with observed radial velocities.

We have made a Monte-Carlo simulation of stars on elliptical orbits beyond the Sun – Galactic center (R_\odot) distance. The semi-major axis (a), eccentricity (e), true anomaly (ν) and argument of pericenter (ω) were chosen randomly with uniform distribution. All orbits were located in the Galactic plane. The mass inside the solar orbit was set to $1.07 \cdot 10^{11} M_\odot$, which corresponds to solar velocity $v_\odot = 240$ km/s.

The rotation velocities were calculated using formulas, that were derived assuming circular orbits. The rotation velocity was calculated from radial velocity (v_r) of star using

$$v(r) = \frac{r}{R_\odot} \left(\frac{v_r}{\sin l} + v_\odot \right), \quad (5)$$

where r is the distance between star and the Galactic center. We want to test the influence of formulas derived for circular orbits applied to stars on elliptical ones.

The semi-major axes in our simulation were distributed from 5 to 25 kpc to avoid truncation effects at $R_\odot = 8$ kpc. The stars with galactic longitudes less than 20° from 0° or 180° were not shown, because the denominator in eq. 5 is too small. A small denominator in equation 5 leads to unphysically large rotation velocities, up to tens of thousands km per second.

The result of the Monte-Carlo simulation for 200 objects is shown on Fig. 2(b). Only objects with the distance 8–20 kpc from Galactic center are shown on the Monte-Carlo simulations plots. The rotation velocities derived from radial velocities have large dispersion and look very similar to the observed rotation velocities from Sofue *et al.* (2009). The rotational velocities on Fig. 2(b) are placed from below Keplerian rotation curve to above flat rotation curve. This is similar to the rotational veloci-

ties in Sofue *et al.* (2009) compilation.

The χ^2 analysis was performed on the Monte-Carlo simulated points in the same way as with open clusters. Although the simulated objects velocities were calculated assuming Keplerian rotation (on elliptical orbits $e=0-0.5$), the $\chi^2 = 1268$ for the agreement with Keplerian rotation curve is almost 8 times larger than $\chi^2_{1-0.005}$. The test of agreement with flat rotation curve $\chi^2 = 13201$ is almost 80 times larger than $\chi^2_{1-0.005}$. So the rotation velocity derived from observed radial velocity in the case of highly eccentric orbits can not be used to distinguish between flat and Keplerian rotation curves.

4 Discussion

The main argument for the flat rotation curve of our Galaxy, given by Sofue *et al.* (2009), is the observation of Sharpless 269 star forming region observed by VERA (VLBI Exploration of Radio Astrometry). Both radial and transverse velocities (Honma *et al.*, 2007) lead to a rotation velocity of ~ 200 km/s. Also the VLBI measurements of parallaxes and proper motions of star forming regions (SFR) published by Reid *et al.* (2014) leads to flat rotation curve. It seems that SFR (maybe all objects in spiral arms) have different rotation velocity than interstellar clouds.

The molecular clouds have the lowest velocity dispersion $\sigma_z = 5$ km/s in the direction perpendicular to the galactic plane, as compared to stars or HII regions. Because of the large cross section they may be better thermalized than stars. Therefore the orbits of molecular clouds may have lower eccentricities than other objects. They match then very well the Keplerian rotation curve in our simulation, similar to velocities observed by Galazutdinov *et al.* (2015).

Eleven directions towards galactic anticenter were observed by Galazutdinov *et al.* (2015). The interstellar clouds are located in Galactic longitudes $184^\circ < l < 190^\circ$. The radial velocities towards these clouds have a standard deviation of 1.8 km/s. We cannot obtain such low dispersion in our simulations, even with circular orbits. The standard deviation of radial velocity for circular orbits in the mentioned longitude range is 3.5–7.2 km/s.

5 Conclusions

The rotation curve derived from observations of old open clusters seems to confirm the observations of Keplerian rotation curve for our Galaxy. The determination of flat rotation curve may be caused by applying the formula derived with the assumption of circular orbits to non-circular ones. The main results are:

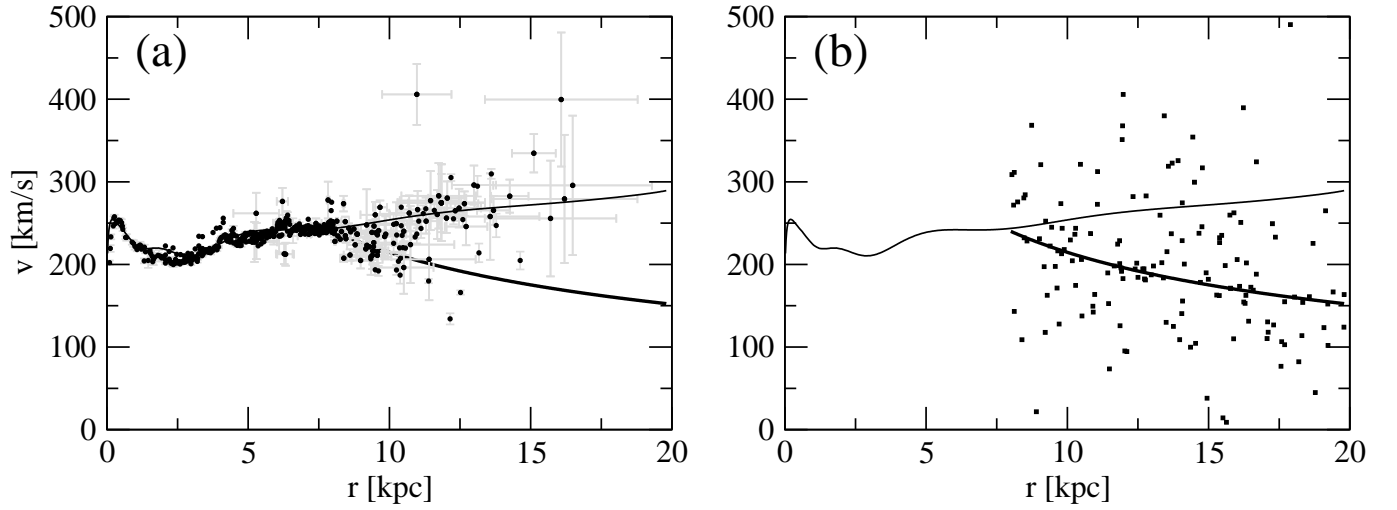


Figure 2: Comparison of the Galaxy rotation curves: **(a)** Points from Sofue *et al.* (2009) derived with tangent point method or from radial velocity. The Sofue *et al.* (2009) data were recalculated using $v_{\odot}=240$ km/s. **(b)** Monte-Carlo simulation of stars on elliptical orbits with eccentricities $e=0-0.5$. The rotational velocities were calculated from radial velocities (eq. 5). The lines show the model of flat rotation curve by Sofue *et al.* (2009) and the Keplerian rotation curve (both for $v_{\odot}=240$ km/s) .

Table 2: Observed (Famaey *et al.*, 2005) and simulated (Monte-Carlo) standard deviations of radial velocity in Galactic anticenter. The square in which we analyze the radial velocities is centered on the Galactic anticenter. The minimum and maximum standard deviation of radial velocity is calculated from 10 Monte-Carlo simulations.

square side [°]	observed std. dev. of v_r [km/s]	Monte-Carlo simulations	
		circular orbits [km/s]	elliptical orbits $0 \leq e \leq 0.6$ [km/s]
6	38.0	3.1–6.2	31.4–51.6
8	43.7	4.1–7.1	28.7–56.7
10	40.7	7.1–9.5	29.3–56.7
12	39.6	8.0–11.8	34.0–50.8
14	40.6	11.1–14.4	20.9–61.2
16	39.0	12.1–15.2	36.8–48.5
18	37.6	12.7–17.8	32.3–57.4
20	37.6	15.4–18.6	35.6–53.9

- The observations of flat or Keplerian rotation curve of our Galaxy can be explained assuming Keplerian rotation, elliptical orbits of stars and almost circular orbits of interstellar clouds.
- The Galactic rotation velocity derived from radial velocity in the case of elliptical orbits with high eccentricities can not be used to distinguish between flat or Keplerian rotation curve.

The Keplerian rotation curve of the Galaxy will have a huge impact on the amount of dark matter in our Galaxy.

References

- Andreuzzi G., Bragaglia A., Tosi M., Marconi G., 2011, MNRAS, **412**, 1265
- Andreuzzi G., Bragaglia A., Tosi M., Marconi G., 2004, MNRAS, **348**, 297
- Bhattacharjee P., Chaudhury S., Kundu S., 2014, ApJ, **785**:63
- Bonifazi A., Tosi M., Fusi Pecci F., Romeo G., 1990, MNRAS, **245**, 15
- Bragaglia A., Tosi M., 2006, AJ, **131**, 1544
- Carraro G., Chiosi C., 1994, A&A, **288**, 751
- Carraro G., *et al.*, 2004, AJ, **128**, 1676
- Carraro G., *et al.*, 2007, A&A, **476**, 217

Carretta E., Bragaglia A., Gratton R., Tosi M., 2004, A&A, **422**, 951

Demers S., Battinelli P., 2007, A&A, **473**, 143

Di Fabrizio L., Bragaglia A., Tosi M., Marconi G., 2001, MNRAS, 328, 795

Famaey B., Jorissen A., Luri X., Mayor M. *et al.*, 2005, A&A, **430**, 165

Fich M., Blitz L., Stark A., 1989, ApJ, **342**, 272

Friel E., *et al.*, 2002, AJ, **124**, 2693

Galazutdinov G., Strobel A. *et al.*, 2015, PASP, **127**, 126

Gratton R., Contarini G., 1994, A&A, **283**, 911

Guetter H., 1993, AJ, **106**, 220

Honma M., Bushimata T., Choi Y.K. *et al.*, 2007, PASJ, **59**, 889

Honma M., Nagayama T., Ando K. *et al.*, 2012, PASJ, **64**, 136

Honma M. *et al.*, 2015, PASJ, **67**, 70

Honma M., Sofue Y., 1997, PASJ, **49**, 539

Janes K., Phelps R., 1994, AJ, **108**, 1773

Marconi G., Hamilton D., Tosi M., Bragaglia A., 1997, MNRAS, **291**, 763

Milone A., 1994, PASP, **106**, 1085

Moni Bidin C., Carraro G., Méndez R.A., Smith R., 2012, ApJ, **751**, 30

Reid M.J., Menten K.M. *et al.*, ApJ, **783**, 130

Scott J., Friel E., Janes K., 1995, AJ, **109**, 1706

Sestito P. *et al.*, 2006, A&A, **458**, 121

Schönrich R., Binney J., Dehnen W., 2010, MNRAS, **403**, 1829

Sofue Y., Honma M., Omodaka T., 2009, PASJ, **61**, 227

Sofue Y., 2016, arXiv:1608.08350

Tosi M., Bragaglia A., Cignoni M., 2007, MNRAS, **378**, 730

Tosi M., Marconi G.L., Focardi P., 1991, AJ, **102**, 951

Yong D., Carney B., Teixeira de Almeida M.L., 2005, AJ, **130**, 597